

Uncertainty in Measurement

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Abstract

Measurements of physical quantities are the corner stone upon which we humans have built the scientific perception of the world. Measurements are the distinctive means to tell the scientific truth apart from any other approach to knowledge. The fundamental concepts of measurement and uncertainty in measurement have been analysed with reference to authoritative documents produced by the International Bureau of Weights and Measures (BIPM). The need for the introduction of the concept of uncertainty and its theoretical implications are analysed. The practical consequences in the development of industrial products have been illustrated for a specific measurement in proton exchange-membrane fuel cell assembly. A short critical analysis of the relationship between the evaluation of uncertainty in measurement and intelligent systems led then to a few open questions.

Keywords: fuel cell, GUM, metrology, PEM, PUMA, uncertainty, VIM

1. Introduction

The fact that intelligent systems have been specifically introduced to overcome the difficulties in handling vagueness and qualitative knowledge in computational environments has generated a misconception quite widespread: once a quantity has been measured, then all the vagueness have vanished because the quantity is described by a number. By contrast, any measurement result is inherently uncertain. Quantifying this uncertainty is the theme of this chapter.

The chapter is based on three of the most authoritative sources of reference: 'The Guide to the Expression of Uncertainty in Measurement' (GUM) [1], 'The International Vocabulary of Metrology' (VIM) [2] and 'The International System of Units' (SI), also known as the SI Brochure [3]. The concepts defined in these documents are analysed and illustrated with an example drawn from the assembly of a proton exchange membrane fuel cell (PEMFC).

The main components of a proton exchange membrane fuel cell (PEMFC) are described in the next section. In this way, examples from PEMFC manufacturing can be introduced in the following sections. In Section 3, the concept of measurement is explored. Reference is made to its fundamental components: the measurand, the reference and the measurement model. In Section 4, the definition of uncertainty in the GUM and in the VIM is discussed. Then, a method of analysis is introduced and illustrated with an example referring to a PEMFC critical measurement. In Section 5, some ideas about the relationship between uncertainty in measurement and intelligent systems are briefly presented. Conclusions are drawn thereafter.

2. Fuel cell components

The main components of a fuel cell are illustrated in the schema of **Figure 1**. A cell provides a voltage of less than 1 V in typical working conditions. Multiple cells are usually connected in series in a stack to increase the voltage to a level suitable for the load that is intended to power.

The bipolar plates (BPPs) represented in **Figure 1** are typically made of metal, graphite or composites. Their primary function is to support the cell and to provide electrical contact with neighbouring cells in the stack. A set of channels may be present on a BPP to convey the reactant gasses onto the gas diffusion layer (GDL). This set of channels is often called a flow field.

GDLs are thin porous sheets inserted to provide a pathway for the gaseous reactants to diffuse evenly from the plates to the membrane electrode assembly (MEA). GDL sheets also take away the water produced in the electrochemical reaction at the cathodic MEA surface and residue of the MEA hydration from the reaction area. A GDL must offer little resistance to the passage of electrons, to enable them to reach the BPP's from the electrochemical reaction sites. These sheets are usually made either of carbon paper or carbon cloth. The first are hard and brittle, with negligible compressibility and generally thinner than the second, which are flexible and can sustain higher levels of compression when assembled in the stack. Therefore, paper-based GDL's need care in handling to avoid chipping and tighter tolerances in the stack due to the poor compressibility. Instead, the compressibility of cloth-based GDLs enables them to be elastically deformed. GDLs may also have microporous layers (MPLs) and polytetrafluoroethylene (PTFE) hydrophobic coatings to balance the requirement of retaining some water to hydrate the MEA in order to keep it conductive with the requirement of maintaining the micropores open for the gaseous reactants to diffuse.

Two variants of MEAs are generally used: three-layer MEAs, also called catalyst-coated membranes (CCMs), and five-layer MEAs. Three-layer MEAs are composed by a proton exchange membrane, also known as polymer electrolyte membrane (PEM), and two catalyst layers. Common membranes are made of an ion-conducting polymer (ionomer) that, when conveniently hydrated, are selectively permeable only to cations while having high electronic resistivity. PEM has also the function of keeping the fuel (hydrogen) and the oxidant (oxygen in the air) separate. The thickness of PEMs usually varies between 10 and 100 micrometres. A catalyst layer is typically made of a mixture of very thin powders of platinum and carbon powder blended with a ionomer. Catalyst layers are applied on the PEM

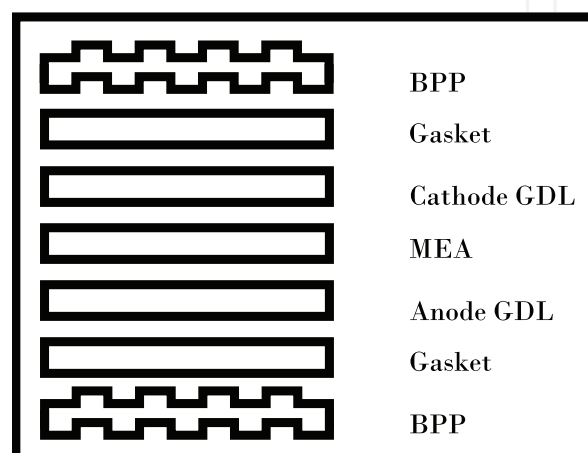


Figure 1. Schema of a proton exchange membrane fuel cell (BPP, bipolar plate; GDL, gas diffusion layer; MEA, membrane electrode assembly).

surfaces and are the sites where the electrochemical reactions occur. The layer where the oxidation of hydrogen occurs is the anode electrode. The layer where the reduction of oxygen occurs is the cathode electrode. The electrodes, i.e. the catalyst layers, must have low electronic resistivity, to enable the reaction-generated electrons to reach the BPP via the GDL at the anode or to be reached by them at the cathode. Five-layer MEAs include also the two GDLs and may differ from CCMs for the sites of application of the catalyst layers, which can be the PEM-facing surface of the GDLs. In this chapter, only CCMs are considered.

The gaskets prevent unexpected leakage of the fluids, i.e. gaseous reactants and water, to the environment and to the other side of the MEA. The first is often referred to as overboard leakage and the second as cross-over leakage. There is always, however, an expected flow rate of the gaseous reagents across the MEA. Such an expected flow rate can be calculated on the basis of a number of variables. Among these are, for example, the MEA thickness and the temperature [4]. The choice of the gasket material depends widely on the operating conditions of the PEMFC (e.g. temperature and pressure of the reactants). Among other materials, gaskets can be made of PTFE or of elastic polymers, e.g. silicone.

With this chapter, a video has been provided which displays a graphical simulation of a PEMFC automated assembly system. The simulation shows the stations where the anode GDL and the gasket are placed onto the BPP and the station where the gap between anode GDL and gasket is inspected. The inspection is based on a vision system. The video is part of the simulation studies carried out by Mr. David Urquhart of the WMG Automation Systems research group of the University of Warwick (UK), within the scope of the EU-funded research project DigiMan. The video is available at the following link: <https://bit.ly/2Ja1W8Z>

3. Fundamentals

Measurement is any experimental process aimed at obtaining one or more number and reference pairs that can be attributed to a property of a body, a phenomenon or a substance (cf. Sections 1.1, 1.19, 2.1 in [2]). This property is called a quantity and its magnitude is defined as the number and the reference considered together. The reference typically is a measurement unit (e.g. the kilogramme, when measuring a mass), but it can be a measurement procedure (e.g. Rockwell C, when measuring hardness) or a reference material (e.g. the concentration of luteinizing hormone in a specimen of human blood plasma, cf. Sections 1.1 and 1.19 in [2]). The measurement unit is a quantity selected conventionally to which any other quantity of the same kind can be compared. The result of this comparison is called the ratio of the two quantities and is expressed as a number (Section 1.9 in [2]).

The above definitions suggest that the following circumstances are necessary for a measurement result not to be intrinsically uncertain:

1. The quantity intended to be measured should be defined without any indeterminacy. This quantity is called the measurand (Section 2.3 in [2]).
2. The reference, in particular the unit of measurement, should have an unambiguous magnitude.
3. The knowledge of which quantities are influencing the measurement and the effects of these quantities on the measurement result should be complete. For example, it should always be possible to compare the measurand and the measurement unit so that no indeterminacy is present in the numerical quantity value (cf. Section 1.20 in [2]).

Unfortunately, none of these conditions holds, as it is described in Sections 3.1, 3.2 and 3.3, respectively.

3.1 Measurand

To define unambiguously a measurand, an infinite amount of information is needed. This unavoidable intrinsic vagueness in the definition of a measurand is called definitional uncertainty (cf. Section 2.27 in [2]). An example can clarify. In PEMFC, if the GDL-gasket gap width is defined as ‘the length of a segment with extremes P_g^* and P_{GDL}^* respectively on the gasket and GDL straight edges’, then there are infinite ways in which each of the two extremes can be chosen. The example is illustrated in Figures 2 and 3, where a distance satisfying the measurand definition above is shown.

A range of different choices can be made when associating geometric entities, which are abstract concepts of the rational world, to entities of the sensory world.

In the schema of Figure 3, the representation of two lines is associated with the GDL and the gasket boundaries, respectively. A line, by definition, is an entity without any width. So it does not exist in the sensory world, because it cannot be perceived. It can only be represented in an approximation.

For the same reason, in Figure 3, there are only two representations of two straight lines in the visible world and not two real straight lines, which are abstract concepts existing only in the human mind. If a straight line representation is on a plane, as in this case, then it needs to occupy a surface portion to be perceived; if it is in space, then, for the same reason, it needs to occupy a volume region.

How then to identify unambiguously in the sensory world a point P_g^* on the straight line l_g^* associated with the gasket boundaries? It is not possible, because



Figure 2. GDL (A), gap (B), gasket (C), edges (d), straight line fitted to each edge (l_g and l_{GDL}).

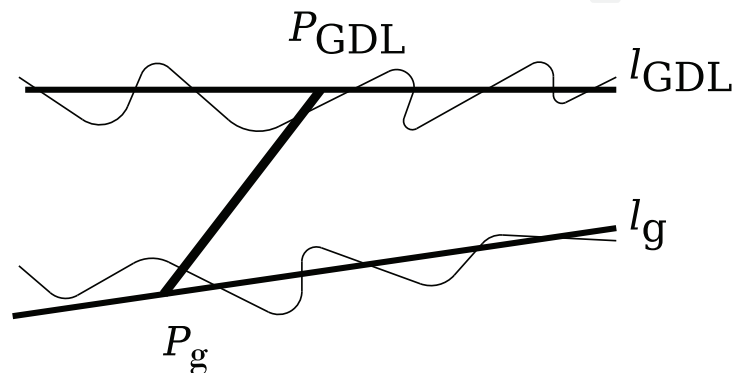


Figure 3. A schema of a gap where the ‘length’ $P_g P_{GDL}$ realises the given definition of gap width. The thin lines represent the edges.

neither the point nor the line exist in the sensory world. The surface portions P_g and l_g , respectively, representing P_g^* and l_g^* can however be identified. Yet each of these surface portions has an extension, which can be thought of as made up of infinite points. Which point to select between this infinity cannot be determined. The same reasoning applies to P_{GDL}^* and l_{GDL}^* . It then follows that the distance between P_{GDL}^* and l_{GDL}^* , i.e. the length of the segment joining the two points, cannot be determined unambiguously in the sensory world. The gap width cannot be defined without indeterminacy.

In **Figure 3**, $P_{GDL}P_g$ represents an infinity of lengths. If the figure is magnified enough, the surface area representing the segment is apparent and so is therefore the infinity of lengths. For this reason, quotation marks have been used in the caption for the term length.

The representations P_{GDL} and P_g can then be chosen in infinite ways on the lines while still complying with the given definition of gap width. This indeterminacy can, however, be removed by specifying further the measurand. For example, the measurand definition can also prescribe that the points P_g^* and P_{GDL}^* are chosen so that their distance is minimal.

Additional detail may be included in the measurand definition to make its realisation in the sensory world less vague. But how much detail? When to stop adding?

A strategy is to define a parameter that expresses the vagueness of the measurement result of the measurand that is about to be defined, for example, a standard deviation, and then to define jointly the measurand and an upper limit for the just defined parameter. If this upper limit is not exceeded, it makes the measurement result fit for purpose. When expressed as a standard deviation, this parameter is called standard uncertainty $u()$ (Section 2.30 in [2]). Its upper limit is referred to as the target uncertainty u^* (Section 2.34 in [2]).

The kind of information contained in a measurement definition is ideally a balance between the need of representing the intended purpose of the measurement result and the need of performing the measurement.

For example, in product design, the specification of the geometrical product characteristics are established by designers for a product to fulfil an intended purpose (e.g. functional, aesthetic, safety-related, regulatory). Often this purpose is referred to as the design intent. Designer product specifications should however account for the limits of available manufacturing and verification processes (sometimes they do not). Providing objective evidence of conformity of a product to its specification is called verification (cf. Section 2.44 in [2]). A verification where product requirement specifications are proved to be adequate for the intended purpose is called validation (cf. Section 2.45 in [2]). The objective evidence relied upon in verification of geometrical product characteristics is provided by measurement.

In the gap width case, for example, a designer is given the information that if the GDL overlaps with the gasket, an overboard leakage of some significance is likely to occur. He or she therefore specifies a lower limit to the minimum gap width. The metrologist who is called to verify the conformity of a gap width to this specification needs to know how to associate the boundaries of the GDL and the gasket (sensory world) to two edges. He or she then needs also to associate a straight line to each of the two edges and to find on them two points at minimum distance. The detail of how they accomplish this depends on the specific characteristics of the measurement they select.

As the example shows, a translation is needed into a practical measurand definition that however does not void the verification of the geometric characteristic.

To facilitate this translation process, the geometrical product specification system of standards (GPS) has been established by the ISO. More formally, the aim of the ISO GPS system is ‘to describe certain workpiece characteristics through some of the different stages of its life cycle (design, manufacture, inspection, etc.)’ (cf. Section 2 in [5]).

3.2 References

Units are the most typical reference used in a quantity value. Hence, they are discussed in this section. Adaptation may be needed if a measurement procedure or a reference material is used as reference of a quantity value. The units of measurement do not have an unambiguous unique magnitude. To support this statement, the concept of ‘definition of a unit’ must be distinguished and kept apart from the concept of ‘realization of a unit’, as explained in the SI Brochure (cf. Sections 1 and 2.2 in [3]). A measurement unit is a quantity that is conventionally defined so as it has solid theoretical foundations and it enables measurements as reproducible as possible. The realisation of a unit is instead a process where a quantity value is associated to a quantity of the same kind as the unit and that fulfils the definition given for the unit. A realised unit is a quantity existing in the sensory world and not just on the paper as the unit definition. The process of unit realisation is made clear by referring to the primary methods of realisation. For a method of unit realisation to be called primary, it needs to allow ‘a quantity to be measured in a particular unit directly from its definition by using only quantities and constants that themselves do not contain that unit.’ (Appendix 4 in [3]). This means that bringing the definition of a unit in existence into the sensory world requires a measurement where the measurand is the unit to be realised.

If a measurement is involved in realising a unit, then the vagueness of a realised unit is the same as that of the measurement that realises it. To limit this vagueness, the realising measurement for the definition of a base unit is specified in a document called a *mise en pratique*. (see Appendix 2 and Section 2.31 in [3]). *Mises en pratique* are only published in electronic form to facilitate frequent revision.

3.3 Measurement model

A measuring system is any set of devices that is designed to generate measured quantity values (cf. Sections 3.2 and 2.10 in [2]). Typically, the nature of the interaction measurand-measuring system cannot be isolated from other quantities characterising the conditions in which the measurement takes place.

For example, when measuring the gap width between gasket and GDL with a vision system, the measurement result is not only a function of the gap but also of other quantities and conditions. Among these, there may be the temperature and humidity of the air affecting the PEMFC component size, the colours of the PEMFC components, the light conditions, the camera (e.g. field of view, magnification and resolution) and the algorithms used to process the acquired images.

This interdependence between quantities is captured by ‘a mathematical relation among all quantities known to be *involved* in a measurement’ which is called in the VIM the measurement model (cf. Section 2.48 in [2]). Namely, it holds:

$$h(Y, X_1, X_2, \dots, X_n) = 0. \quad (1)$$

In Eq. 1, Y is the measurand that is also called output quantity of the model to highlight that the value of Y is calculated with the measurement model 1 when the

quantity value of X_1, X_2, \dots, X_n is known. The quantities X_1, X_2, \dots, X_n are correspondingly called the input quantities of the measurement model (cf. 2.50 in [2]). The value of the input quantities is known either by measurements or by other means like calibrated measurement standards, certified reference materials, reference data **obtained** manufacturer's specifications, handbooks and certificates. Often Eq. 1 can be explicitly defined as follows:

$$Y = f(X_1, X_2, \dots, X_n). \quad (2)$$

In Eq. 2, the function $f(X_1, X_2, \dots, X_n)$ is referred to as measurement function (cf. Section 2.49 in [2]).

This situation generates indeterminacy of the measurement in at least two different ways: in the selection of the input quantities and in their effect on the measurement result.

The input quantities in a measurement model are not uniquely known. Different people may consider different quantities to be relevant in a measurement on the basis of their knowledge of the phenomena involved in the process of measurement. The expression 'all the quantities known to be *involved* in a measurement' that appears in the VIM measurement model definition does not identify a unique set of input quantities in its implementation.

The VIM definition appears to suggest that an effort should be made to include in the model all the quantities believed to influence the measurement result, not just those influencing it the most.

The GUM refers to the inclusion in the model of 'every quantity that can contribute a *significant* component of uncertainty to the measurement result' (4.1.2 in [1]).

But how can a component of uncertainty contribution to the measurement result be considered *significant* if it is not first included in the model (GUM case)? On the other hand, how to know if a quantity is *involved* in a measurement if it is not first included in the model (VIM case)?

This difficulty may be overcome by considering the selection of input quantities on the basis of knowledge available prior to the formulation of the model. There is an element of subjectivity in this selection that ultimately relies on honesty and professional skill of those who are building the model (3.4.8 in [1]).

Some of the input quantities may then in their turn 'be viewed as measurands and may themselves depend on other quantities' (4.1.2 in [1]). That is to say, some of the quantities are the output of another measurement model. A measurement model is then a hierarchy of different models nested one in the other. How many levels of hierarchy do exist depends on the specific measurement. The levels, however, must be finite, because they ultimately reach the realisation of the definitions of the base units (see the SI Brochure for the recently changed definition of base unit [3]).

The measuring model $h(\dots)$ (or function $f(\dots)$) is typically not known analytically, barring those cases when some physical law describing the measurement is available. Ideally, the effect of an input quantity on the output is determined by an experimental investigation. The extension of the investigation is a balance between its cost and the intended use of the measurement result.

For example, the effect of the air humidity on the GDL-gasket gap width could be estimated by conducting an experiment if the cost of the experiment was affordable and the width measurement result needed to be confidently relied upon. But what if that cost was not affordable? Should the model builders give up to their prior knowledge that led them to include air humidity in the model because they cannot estimate its effect on the gap width?

Perhaps, an option is to rely on the skill and scientific knowledge of the model builders in estimating the sensitivity of the gap width to the humidity on the basis of their prior knowledge that led them to include the humidity in the first place. But then, where would it be the experimental validation that is typical of any scientific investigation? The issue is controversial.

When using prior knowledge to determine the effect of the humidity on the gap width, the specialists building the model may for example subjectively adjudge that this effect is negligible. They may then be so confident in their judgement that they model the air humidity effect with a constant in the model. Differently, if they are less confident, they can model the effect as a random variable with a mean of small value and a standard deviation subjectively attributed (for example, by inferring it from a survey in handbooks or other reputable sources). If the constant or the mean of the random variable was zero, someone may wonder why they have included the humidity in the model. The sole reason would be to show due diligence in their analysis.

4. Uncertainty

The argumentation presented so far is aimed to make the intrinsic indeterminacy of measurement results apparent.

In the GUM, this indeterminacy or vagueness that expresses a doubt about the result of a measurement is referred to as uncertainty (cf. Section 2.2.1 in [1]). In the same document, the term uncertainty is, however, also used in a more specific way to designate a parameter providing a quantitative measurement of this generic concept of doubt; namely in the GUM, uncertainty is defined as a ‘parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand’ (cf. Section 2.2.3 in [1]).

In the VIM instead, measurement uncertainty is defined as a ‘non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used’ (cf. Section 2.26 in [2]).

Typically this parameter is the standard deviation of a probability density function that models the incomplete or partial knowledge of the measurand achievable with measurements. This partial knowledge is described respectively by the expressions ‘reasonably attributed’ and ‘based on information used’ in the two definitions.

In the error approach, as the VIM puts it, ‘a true quantity value is considered unique and, in practice, unknowable’ (cf. Section 2.11, note 1 in [2]).

The uncertainty approach is to recognise that owing to the inherently incomplete amount of detail in the definition of a quantity, there is not a single true quantity value but rather a set of true quantity values consistent with the definition. However, in principle and in practice, this set of values cannot be known (see Appendix D in the GUM [1], D.3 in particular). Then, even if an imaginary measurement is capable of producing measurement results of a measurand without any indeterminacy, that measurand would still be known with vagueness.

The introduction of a probability density function of a measurand Y and of an input quantity X_i is the same to say that these quantities are represented by a random variable, whose realisations y_i and x_{ij} are all their possible observations.

4.1 Uncertainty analysis

This section has similarities with the BS EN ISO 14253-2:2011 ‘Procedure for Uncertainty Management (PUMA)’ [6]. However, the analysis conducted here

adheres more strictly to the GUM: the evaluated uncertainty is not overestimated as it is instead in the iterative PUMA procedure (cf. Section 5 in [6]). A measurement may be seen as an iterative process consisting of seven steps. These steps are listed below and illustrated in the diagram of **Figure 4**.

- **The measurand definition** has been discussed in Section 3.1. The amount of detail to include in the definition is determined. The detail may include ‘physical states and conditions’ (D.1 in [1]). If the target uncertainty test fails in the following step, attempts to satisfy it by modifying the in-between steps within the limits of the resources available are made. If these attempts are ineffective, then further detail may be added to the definition. However, adding detail to the measurand should be consistent with the purpose for which the measurement result is intended to be used.
- **The measurement principle** is the physical, chemical or biological phenomenon on which the measurement is based, as defined in Section 2.4 of the VIM [2]. Once a principle has been chosen, additional characteristics concerning the measurement principle may be added to the steps that follow.
- **The measurement method** is a ‘generic description of a logical organization of operations used in a measurement’ (2.5 in [2]). The category of operations encompassed by the same measurement method is typically large.
- **The measurement procedure** is a description of the measurement with enough detail to allow an operator to perform it. This description is typically a sequence of instructions for the operator. The sequence is sometimes called standard operating procedure (SOP, cf. 2.6 in [2]) and includes a statement of target uncertainty.
- **The measurement model** is established on the basis of the measurand. This concept has been defined in Section 3.3. **Figure 5** displays a fish-bone diagram which is an elaboration of the content from Section 7 of BS EN ISO 14253-2:2011 [6]. It displays a grouping of candidate input quantities. The figure suggests a systematic procedure of input quantity investigation for inclusion in a measurement model for uncertainty evaluation. The model refers to the measurement of a geometric characteristic, which is the case of the gap width. The figure has been produced using qcc, an **r** software package [7].
- **A target uncertainty test** is performed. The measurement uncertainty ($u(Y)$) is first evaluated and then compared with the target uncertainty (u^*). If $u(Y) > u^*$, then all the previous steps are put under scrutiny. The source of

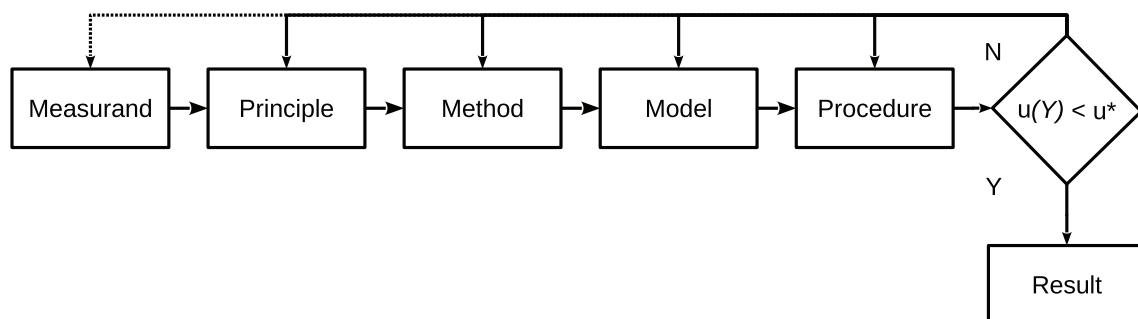


Figure 4. Diagram illustrating the steps of a measurement ($u(Y)$ and u^* are the evaluated and the target measurement uncertainty, respectively).

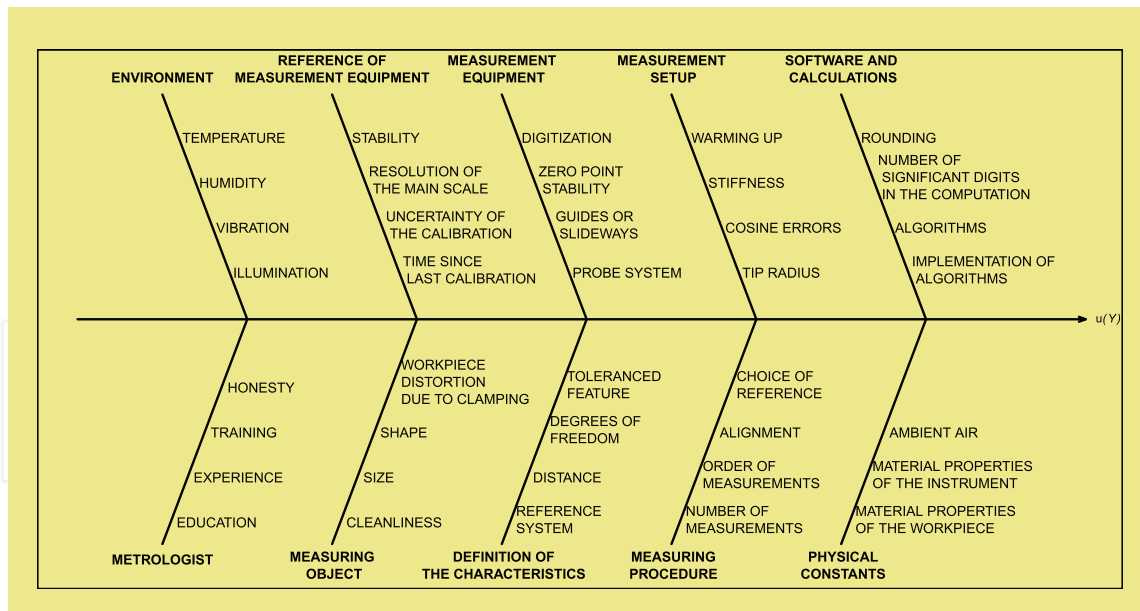


Figure 5. An Ishikawa (fish-bone) diagram displaying a categorical hierarchy of potential input quantities typically considered for inclusion in measurement models for uncertainty evaluation $u(Y)$ of geometric quantities (elaboration from Section 7 of BS EN ISO 14253-2:2011 [6]).

uncertainty that is found to contribute more to the violation of the target uncertainty constraint or that is known the least is respectively mitigated or further analysed, if possible. If not, the second most severe or less known uncertainty source is considered, and so on. Once one source of uncertainty has been chosen, it is acted upon and the test $u(Y) < u^*$ is run again. The sequence is repeated until $u(Y) < u^*$ or the measurement is recognised incompatible with the given target uncertainty.

- **The measurement result** is presented in a form that also contains an expression of the evaluated uncertainty. As much detail as possible about how the evaluation was performed is recommended by the GUM. Specific guidance is given in its Section 7 [1].

The uncertainty of the measurand Y that appears in the target uncertainty test is ‘evaluated’ and not ‘estimated’. The verb ‘to evaluate’ is used to highlight that the input quantities X_i are typically grouped into two categories. The standard uncertainty of those in the first group is determined by their repeated observation (Type A evaluation, Section 4.2 in [1]). The standard uncertainty of those in the second is instead determined by the ‘scientific judgement based on all of the available information’ (Type B evaluation, cf. Section 4.3 in [1]). In the first case, uncertainty evaluation is based on probability density functions estimated from frequency distribution of observations. In the second, the evaluation is based on probability density functions postulated on the basis of reputable sources of information like handbooks or calibration certificates. In both Type A and Type B evaluations, the complete characterisation of the probability density functions $p(X_i)$ of the input quantities is needed. Complete characterisation means that the mean $E(X_i) = \mu_i$, the standard uncertainty $u(X_i)$ and the distribution type (e.g. normal, triangular, rectangular/uniform) must be made available for each X_i . Then, the measurement function is expanded into a partial sum of the Taylor series around the input quantity means. By applying the definition of variance to this partial sum, the variance of the output quantity is expressed as a sum of the variances and covariances of the input quantities, where each term is multiplied by constants (law of

propagation of uncertainty, E.3 in [1]). These constants are the coefficient of sensitivity.

According to the GUM definition, measurement uncertainty refers to the result of a measurement. If the conditions in which the measurement is carried out are believed to be influencing the result, they have also to be specified: input quantities are introduced in the measurement model to represent them. For example, if multiple measurement runs are necessary to calculate the result, as it is the case when the result is an average, then the repetition settings may enter the model, if believed influential. Typical repetition settings are repeatability and reproducibility conditions (2.20 and 2.24 in [2]). Repetition settings may not be quantities as defined in Section 3, because they represent conditions and not properties expressed as number and reference pairs. They enter the model as random variables. When they are meant to contribute only to the uncertainty of the measurement result, these random variables have location parameter (e.g. mean, median) set at zero and unknown standard deviations.

The statement of the uncertainty $u(Y)$ and of the input quantities that most contribute to $u(Y)$ together with the evaluation of their uncertainty and their combination to give $u(Y)$ is called uncertainty budget (2.33 in [1]). The next section illustrates the uncertainty analysis of the gap width.

4.2 Gap width uncertainty

The steps of the gap width measurement are listed here below.

- **The gap width definition** has been given in Section 3.1 and illustrated in **Figure 3**. The requirement of minimum distance between P_g and P_{GDL} is a part of the definition considered here. The symbol w is used for the measurand. If satisfying the target uncertainty requirement is not practicable with this definition, then a more detailed measurand definition is needed. An example of a new definition is the following: the gap edge is the minimum distance between P_g and P_{GDL} when the straightness of the GDL and gasket edges is $t = 0.05\text{mm}$ (cf. 17.2 in [8] for a definition of straightness). This new definition may provide a measurand with less variation in the gap width. The process of verifying the edge straightness specification may be described by a dedicated input quantity in the measurement model. This variable is in its turn the output of a measurement.
- **The measurement principle** on which the gap width measurement is based is the selective reflection of visible light by the GDL, the gasket and the gap background. For the anode GDL and the cathode GDL, the gap background is respectively the portion in view of the BPP and the MEA. In **Figure 2**, the background was replaced with a white paper sheet. Characteristics like wavelength, intensity, number and locations of the light sources may enter the measurement procedure and measurement model, if needed. But how to ascertain whether there is a need to include them? If they are included, their contribution to the uncertainty of the measured gap width is estimated. Generating the data for an estimation requires an experimental investigation whose the cost may not be affordable. In these cases, a Type B evaluation is performed.
- **The measurement method** of the gap width is the digital image processing of an image where the gap is visible. The gap width definition is realised in this

image. The position and orientation of the camera relative to the gap, the characteristics of the optics and of the CCD sensor all contribute to the captured view of the gap.

- **The measurement procedure** of the gap width depends heavily on the vision system used and its degree of automation. The operator can be a person, a robotic system holding a camera, a computer that runs the image processing algorithms or a combination of all of these. The sequence of instructions in the procedure has therefore to account for these different kinds of operators. To clarify, the case of a fixed camera orthogonally placed above the gap is considered. The acquisition process is completely automated. The light conditions and camera set-up are fixed. The instructions in this case consist of commands written in a computer program. The commands are grouped in modules, whose sequence is illustrated in **Figure 6**. In each single module represented in this diagram, discretionary decisions may be taken in the selection of an algorithm and its parameters. Examples of these decisions are the following: a Canny edge detection algorithm is selected among the many available algorithms; the edges are considered acceptable if they have no more than a predetermined number of pixels groups disconnected from the largest edge; the image filtering is done with a Gaussian filter to reduce the number of disconnected group of pixels, i.e. the occurrence of edge false detection; and straight lines are fitted to the edges using an orthogonal non-linear least squares algorithm (ONLS). As it can be deduced from these examples, the decisions taken in the modules affect the measured gap width. The subjective behaviour of the specialists taking these decisions is reflected in a contribution to the gap width uncertainty.
- **The measurement model** chosen to describe the gap width measurement is given by the following equation:

$$w = \sqrt{c^2(u_{\text{GDL}} - u_g)^2 + a^2c^2(v_{\text{GDL}} - v_g)^2} + e. \quad (3)$$

To enhance readability, the convention used in the example of Section H.1 of the GUM was adopted [1]: random variables are in lowercase italic shape and constants are in the normal lowercase shape. In the vision system, the image coordinate system with coordinates expressed in number of pixels is such as $P_g = P_{\text{GDL}}(u_{\text{GDL}}, v_{\text{GDL}})$ and $P_g = P_g(u_g, v_g)$, c is the calibration factor which is the ratio of an imaged calibration length to the number of pixels contained in it and a is the aspect ratio of a pixel (width over height). The measurement function of Eq. 3 is based on the following assumption: the imaged artefact realising the calibration

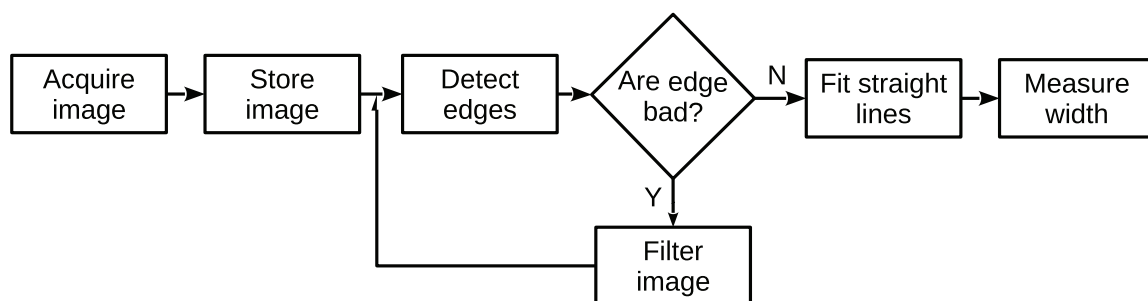


Figure 6. A diagram of the sequence of modules that constitute the measurement procedure.

length needs to be placed so that the calibration length is aligned with the x axis of the image coordinate system.

- **A target uncertainty test** is performed. If the target uncertainty test fails, then one input quantity is selected for a more detailed uncertainty evaluation. The selection criteria are described in Section 4.2. For example, in the vision system the magnification of the lens is the ratio of the length on the image to the length in the scene, i.e. $m = l_{image}/l_{scene}$, where $l_{image} = s n_{CCD}$, with s indicating the pixel size on a CCD sensor and n_{CCD} representing the number of pixels in the imaged length. Then, the following equations holds:

$$c = l_{scene}/n_{CCD} = s/m. \quad (4)$$

To clarify, the case of a CCD sensor with pixel size $6.45 \mu\text{m}$ and a lens magnification 100 would result in a calibration factor 0.0645. A new level of detail is introduced in the original measurement model of Eq. (3) by the nested model of Eq. (4). The uncertainty of the calibration factor c is then evaluated by combining the uncertainty evaluations of s and m .¹

- **The measurement result** is presented in a statement like, for example, the following: ‘the gap width is 0.08 mm with a standard uncertainty $u(w) = 0.014 \text{ mm}$ ’. A report illustrating how the measurement and the evaluation took place would also be attached.

5. Intelligent systems and uncertainty


The relationship between intelligent systems and the uncertainty in measurement is analysed in this section. The concept of uncertainty in measurement has been explored in the previous sections. The concept of an intelligent system is more elusive. It requires first to understand what intelligence means. With intelligence, it is typically intended a set of human rational abilities that include reasoning, learning and adaptation to changing conditions. Yet, which of these abilities are the distinguishing characteristics needed for a system to be called intelligent is controversial. Failing to recognise the differences in the behaviour between an artificial system and a human is often advocated as a criterion for considering the artificial system as intelligent (Turing test [9]).

In uncertainty evaluation, circumstances arise where discretionary decisions of human specialists are necessary. Realising an intelligent system whose behaviour constitutes a reference for the specialists in making these decisions would greatly reduce their discretion. For example, in the definition of the gap width measurand and of its measurement model, a trusted intelligent system would facilitate the task. To be considered intelligent, such a system would need to demonstrate to take decisions independently from human input and not just ‘executing’ a pre-determined behaviour that the system is programmed to have. Conversely, an uncertainty evaluation is purposely carried out to quantify how much trust there is in a measurement result. The question then arises whether an uncertainty analysis where an artificial intelligent system is ‘the specialist’ taking discretionary decision unsupervised by humans can be trusted as a human (or more).

¹ The symbols introduced in this example have not been included in the end-of-chapter symbol list to keep it clear.

A framework to evaluate the uncertainty of an intelligent system providing a measurement uncertainty analysis is needed. No evidence of that has been found in the literature. Research surveyed about the adoption of intelligent systems in measurement uncertainty evaluations dates back to about 10 years ago. An expert system for uncertainty evaluation in analytical chemistry has been developed by Rösslein and Wampfler [10]. Their motivation was to provide a means of performing complex uncertainty evaluations that otherwise would have been too simple for their purpose or too costly. An analysis of how much trust to put into their system has not however been found.

Intelligent systems may then contribute to reduce uncertainty in any measurement phase where parameter-dependant software modules are involved. A parameter, by definition, needs to be given a value that is determined by a specialist. He or she does so drawing from their knowledge. This may leave room for subjective decisions that contribute to the uncertainty. With an intelligent system replacing the judgement of the specialist in the determination of the parameter value, it may seem possible to eliminate that uncertainty. This possibility would require the intelligent system not to be dependant in its turn on other parameters, which is hardly the case.

The situation is illustrated with the edge detection module in the gap width case. If a Canny edge algorithm is used, then two threshold parameters need to be determined. An intelligent system (e.g. a neural network) may be trained on a set of images for this purpose. But this would still have at least one component of uncertainty which is **how** the choice of the training set of images (equivalently, the parameters identifying the training set of images). 

6. Conclusions

Uncertainty as a technical term introduced by authoritative international bodies as a means of representing the intrinsic indeterminacy in measurements has been discussed. The analysis presented in this chapter provides an interpretation of the documents elaborated by these international bodies. The framework defined in these documents is interpreted as a method that makes it possible to organise consistently the knowledge about measurement uncertainty within the limitations of the resources available.

Acknowledging that measurements are always unavoidably uncertain has some profound implications on how humans construct their knowledge about the physical world in science and technology. Measurements are the ultimate source of knowledge in science: any statement to be scientifically accepted must be substantiated by experiments or observations that are expressed in terms of measurement results. If measurement results are inherently uncertain, all that can be inferred from them can be only uncertain. One consequence is, for example, that talking of ‘exact science’ when referring to Physics can be quite prone to misinterpretations. Science may be considered exact only in its methods of dealing with approximations and uncertain or partial knowledge. Stretching this view to its extreme may lead to consider science as an activity with very useful practical effects but with little use in the unambiguous identification of the truth.

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Nomenclature

Symbols

| | |
|------------------------------------|--|
| Y | output quantity in a measurement model |
| y_i | the i th observation or realisation of an output quantity |
| X_i | the i th input quantity in a measurement model |
| x_{ij} | the j th observation or realisation of the input quantity X_i |
| $E(X_i) = \mu_i$ | mean or expected value of X_i |
| $p(\dots)$ | probability density function |
| $h(\dots) = 0$ | measurement model |
| $Y = f(\dots)$ | measurement function |
| $u()$ | standard uncertainty |
| u^* | target uncertainty |
| $l_{\text{GDL}}^*, l_{\text{g}}^*$ | GDL and gasket straight edges |
| $l_{\text{GDL}}, l_{\text{g}}$ | representations of the straight edges of GDL and gasket in the sensory world |
| $P_{\text{GDL}}^*, P_{\text{g}}^*$ | points defining the gap width |
| $P_{\text{GDL}}, P_{\text{g}}$ | representations in the sensory world of the points defining the gap width |
| $(u_{\text{GDL}}, v_{\text{GDL}})$ | coordinates of P_{GDL} in the image reference system |
| $(u_{\text{g}}, v_{\text{g}})$ | coordinates of P_{g} in the image reference system |
| c | calibration factor, i.e. length of a pixel width in units of length |
| k | image aspect ratio |
| m | lens magnification |
| s | physical size of a pixel on a CCD chip |

Abbreviations

| | |
|-------|--|
| BIPM | Bureau International des Poids et Mesures (International Bureau of Weights and Measures) |
| BPP | bipolar plate |
| CCM | catalyst coated membrane |
| GDL | gas diffusion layer |
| GPS | geometrical product specification |
| GUM | Guide to the Expression of Uncertainty in Measurement |
| ISO | International Organisation for Standardisation |
| MEA | membrane electrode assembly |
| MPL | microporous layer |
| ONLS | orthogonal non-linear least squares |
| PEM | proton exchange membrane (polymer electrolyte membrane) |
| PEMFC | proton exchange membrane fuel cell |

| | |
|------|---|
| PTFE | polytetrafluoroethylene |
| PUMA | procedure for uncertainty management |
| SI | Le Système International d'unités (The International System of Units) |
| SOP | standard operation procedure |
| VIM | International Vocabulary of Metrology |

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